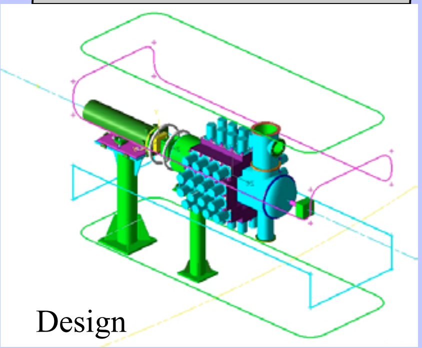
Precision Measurement of Parity Violation in Polarized Cold Neutron Capture on the Proton: the N P D γ Experiment

at the Los Alamos Neutron Science Center

Bernhard Lauss
UC Berkeley

for the NPDGamma Collaboration



PANIC'05 Conference
Santa Fe, NM
October 24-28, 2005

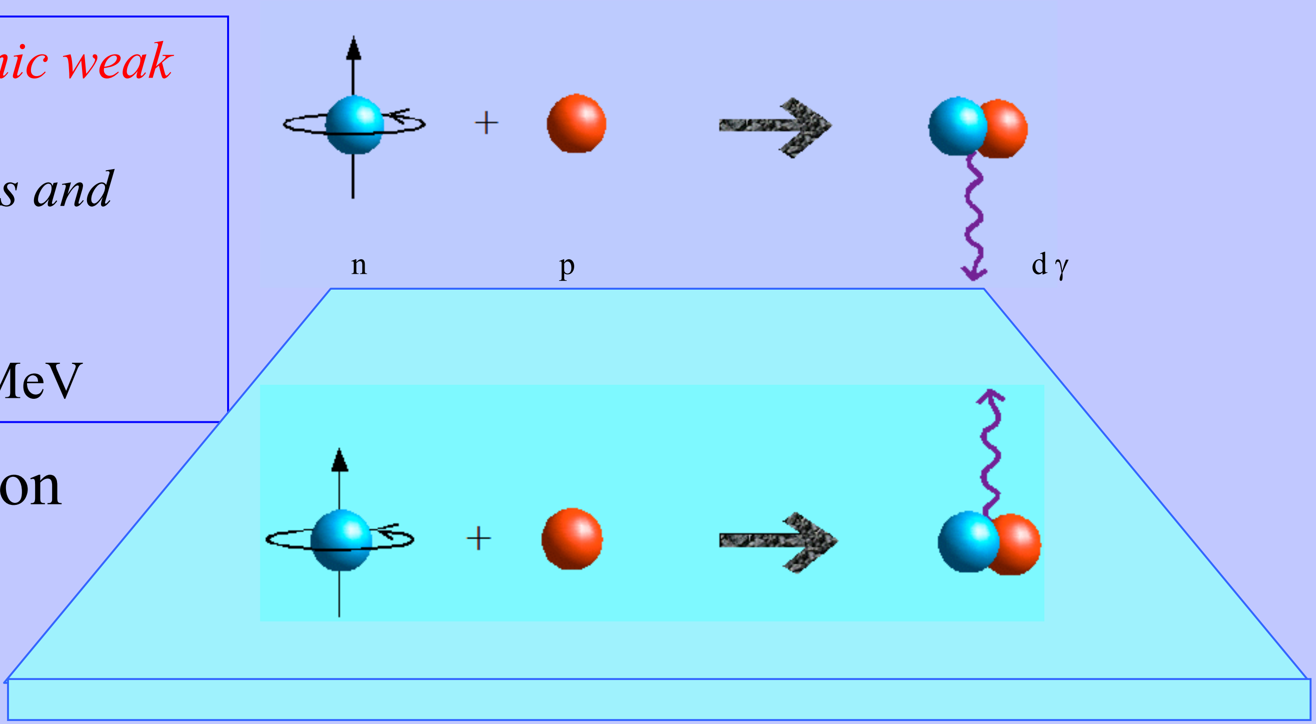
What kind of physics do we study in NPDγ ?

The Process

We study is the *hadronic weak interaction* between *spin-polarized neutrons and protons* in the

$$\vec{\mathrm{n}} + \mathrm{p} \to \mathrm{d} + \gamma$$

reaction. $E_\gamma = 2.2$ MeV



Parity Transformation

$$\Psi(\vec{r}) \to \Psi(-\vec{r})$$

flip n-spin

the correlation between neutron spin and photon momentum

$$\langle \vec{s}_n \cdot \vec{k}_\gamma \rangle$$

is odd under parity transformation

($\vec{k}_\gamma$ changes sign, $\vec{s}_n$ does not)

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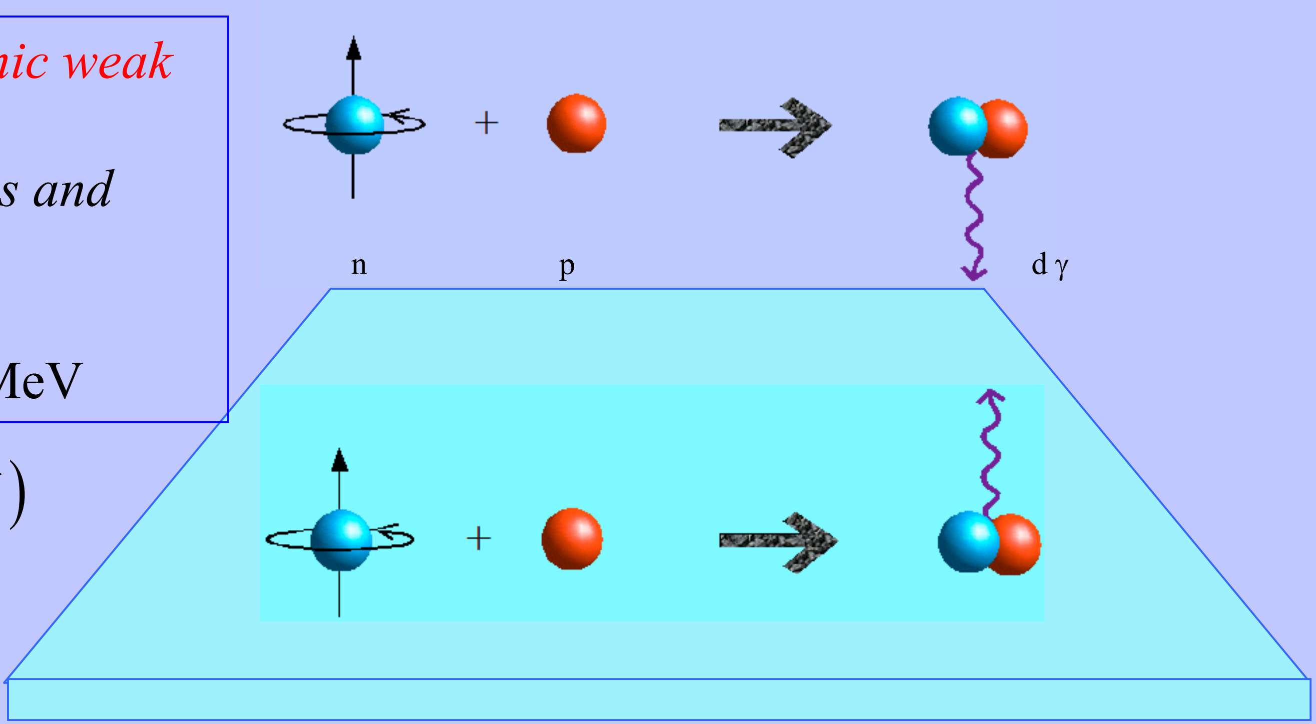


$$\Psi(\vec{r}) \rightarrow \Psi(-\vec{r})$$

flip n-spin

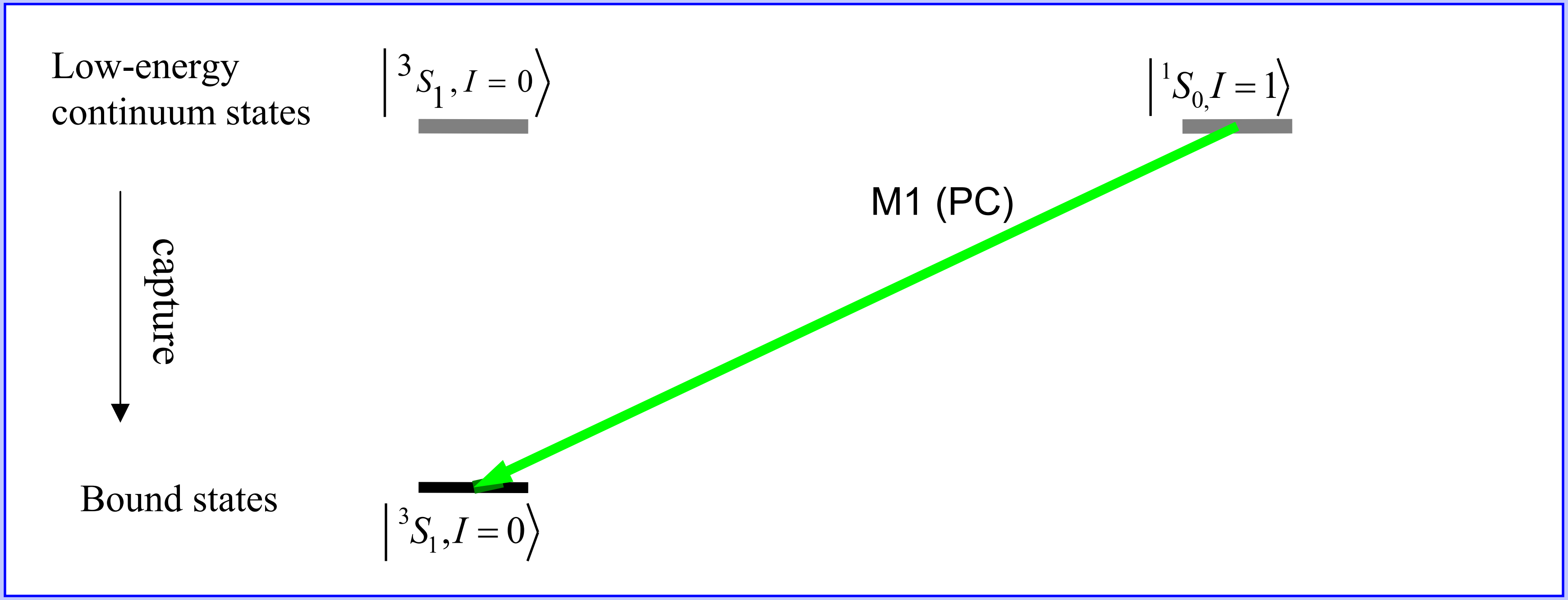
Weak-Interaction violate parity

If the up/down ? rates differ, parity is violated !

strength of strong / weak interaction ~ 10^{-8}

NPDG measures A_γ, the parity-violating asymmetry in the distribution of emitted γ's.

Simple Level Diagram of *n-p* System



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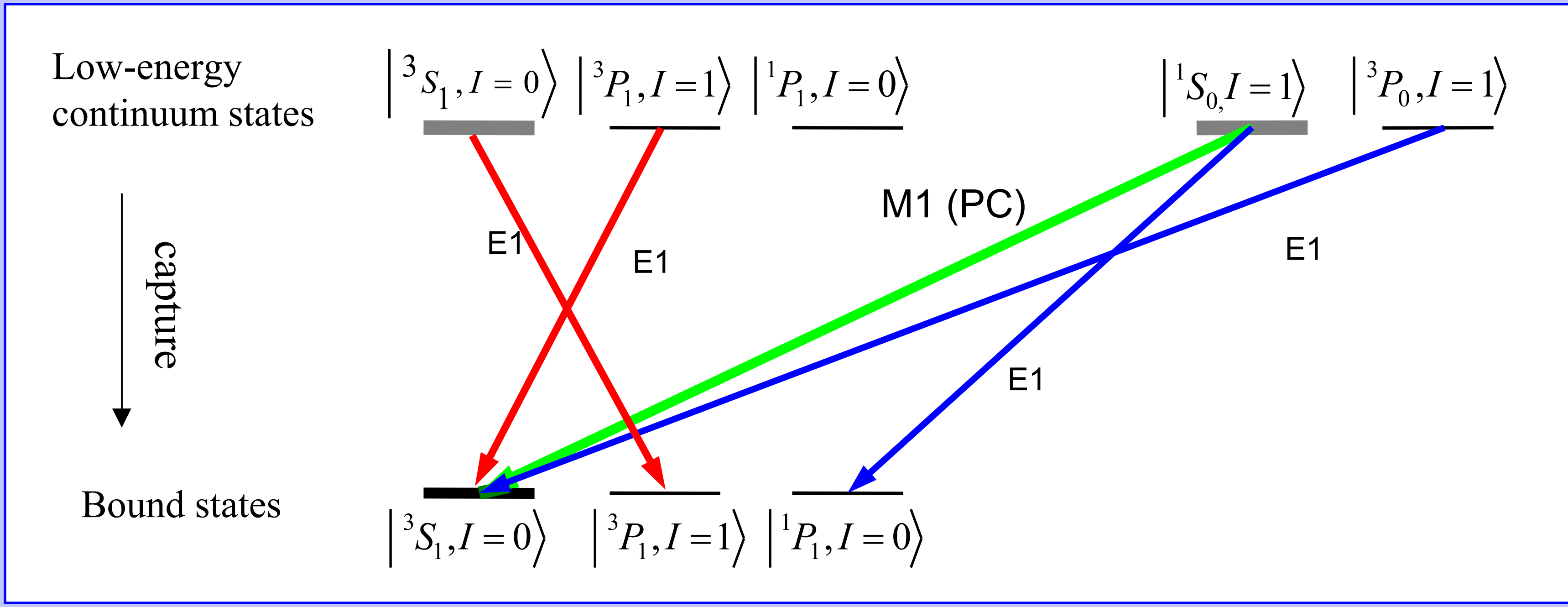


$\vec{n} + p \rightarrow d + \gamma$ is primarily sensitive to the ? I = 1 component of the weak interaction

- Weak interaction mixes in *P* waves to the singlet and triplet *S*-waves in initial and final states.
- Parity conserving transition is *M*1.
- Parity violation arises from mixing in *P* states and interference of the *E*1 transitions.
- A_γ is coming from ${}^3S_1$ - ${}^3P_1$ mixing and interference of *E*1-*M*1transitions - ΔI = 1 channel.

Mixing amplitudes:

$\left\langle {}^3S_1 \middle| V_W \middle| {}^3P_1 \right\rangle; \Delta I = 1$ π exchange

$\left\langle {}^3S_1 \middle| V_W \middle| {}^1P_1 \right\rangle; \Delta I = 0$ ρ exchange

$\left\langle {}^1S_0 \middle| V_W \middle| {}^3P_0 \right\rangle; \Delta I = 2$

The Hadronic Weak Interaction

Nucleon interaction takes place on a scale of 1 fm -- short range repulsion. Due to the heavy exchange particles, the range of $W^{\pm}$ and Z^0 is 1/100 fm, weak interaction probes quark-quark interaction and correlations at small distances.

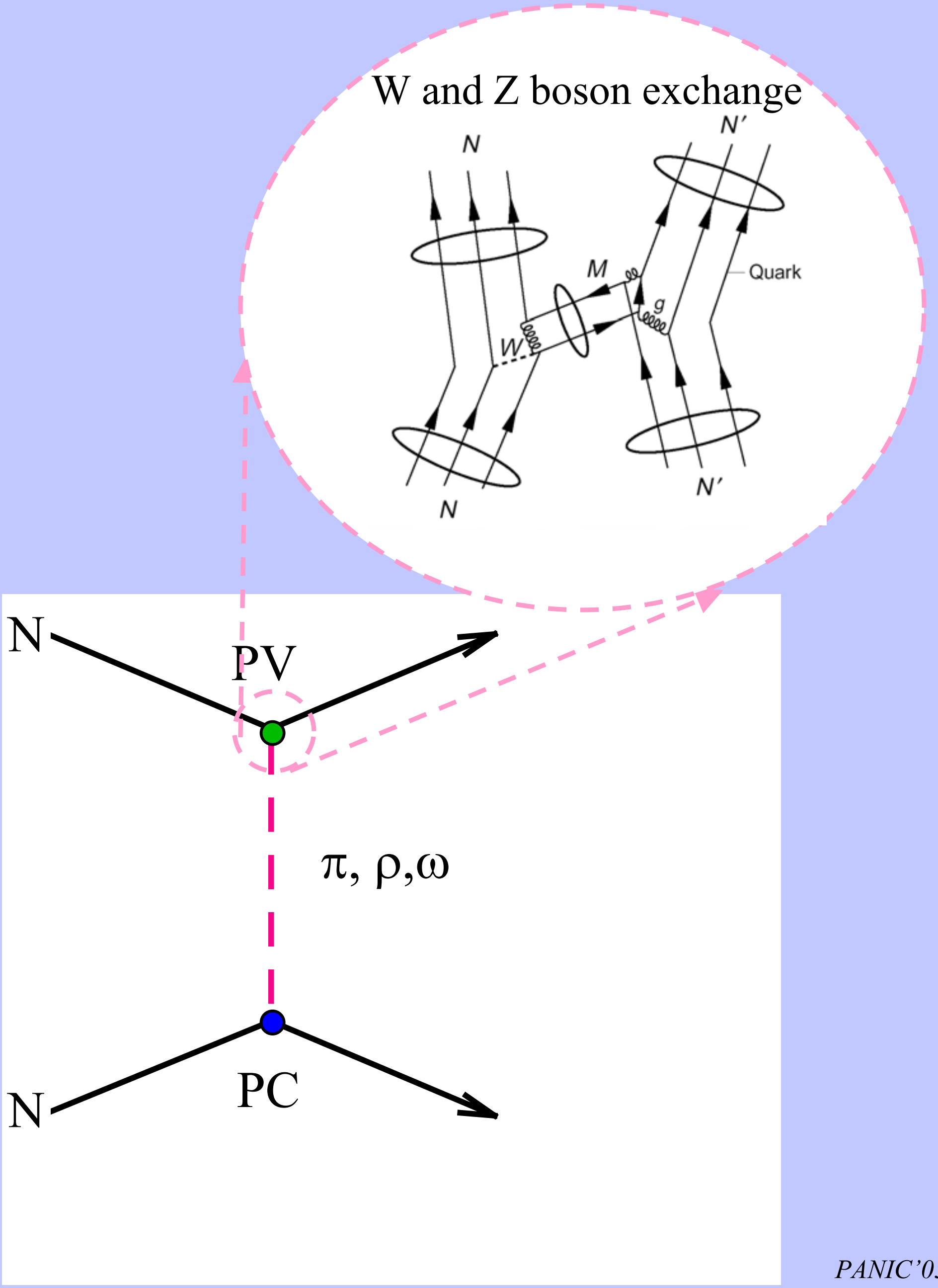
At low energies N-N weak interaction modeled as meson exchange with one strong PC vertex, one weak PV vertex.

classical **DDH - Model**

Desplanque, Donohue, Holstein 1980

The weak PV couplings contribute in various mixtures and a variety of observables:

$$\boxed{f_\pi^1, h_\rho^0, h_\rho^1, h_\rho^{1'}, h_\rho^2, h_\omega^0, h_\omega^1}$$



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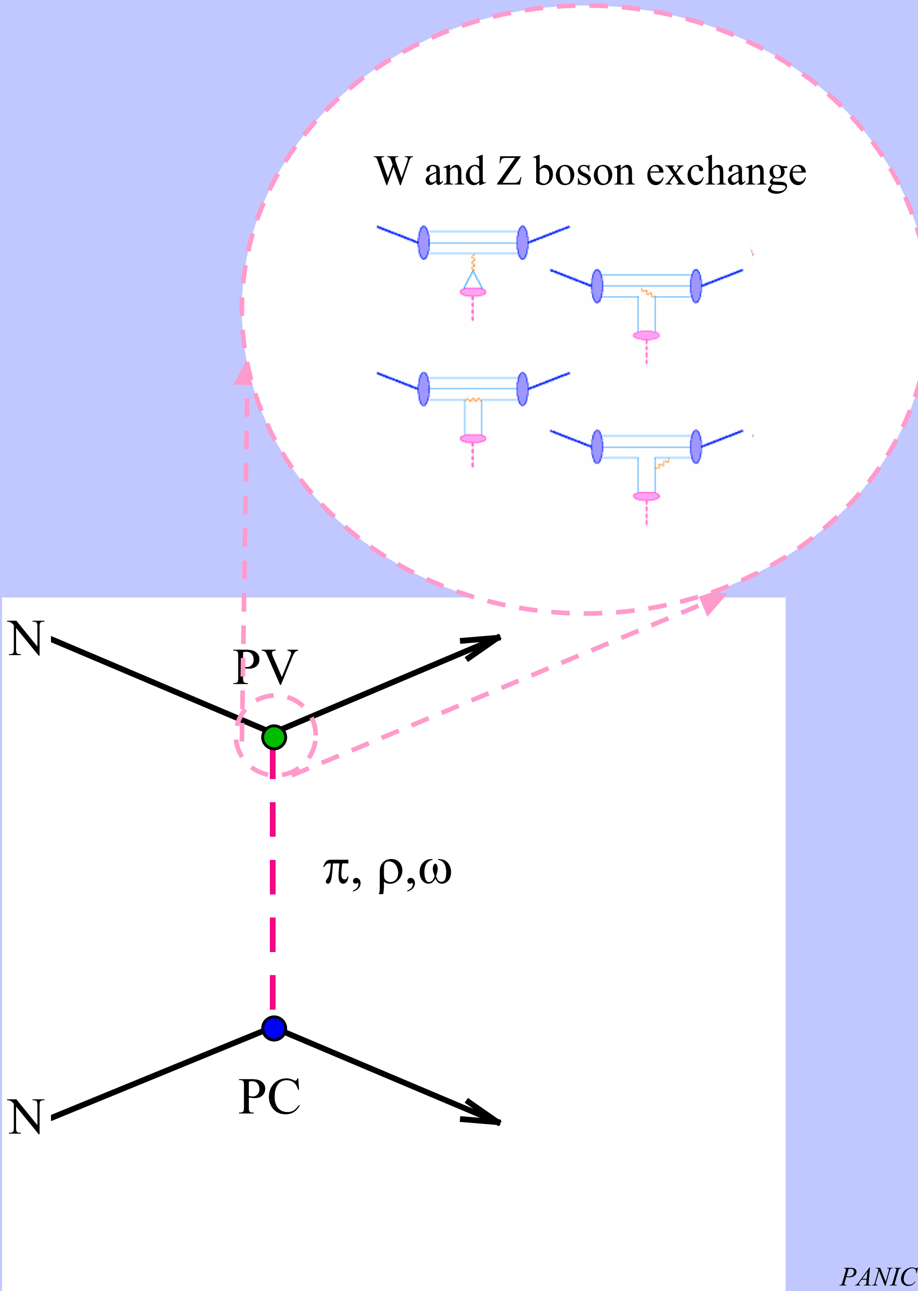
new model independent EFT approach by *Ramsey-Musolf, Holstein, van Kolck, Zhu and Maekawa* describes processes in terms of low-energy constants/amplitudes describing short-range force and pion interaction (EFT: 5 low-energy PV amplitudes without explicit pions , 8 with explicit pions) - calculate these from first principles



Constraints on Weak N-N Coupling

- $\vec{n} + p \rightarrow d + \gamma$ is a clean measurement of a single parameter f_p:

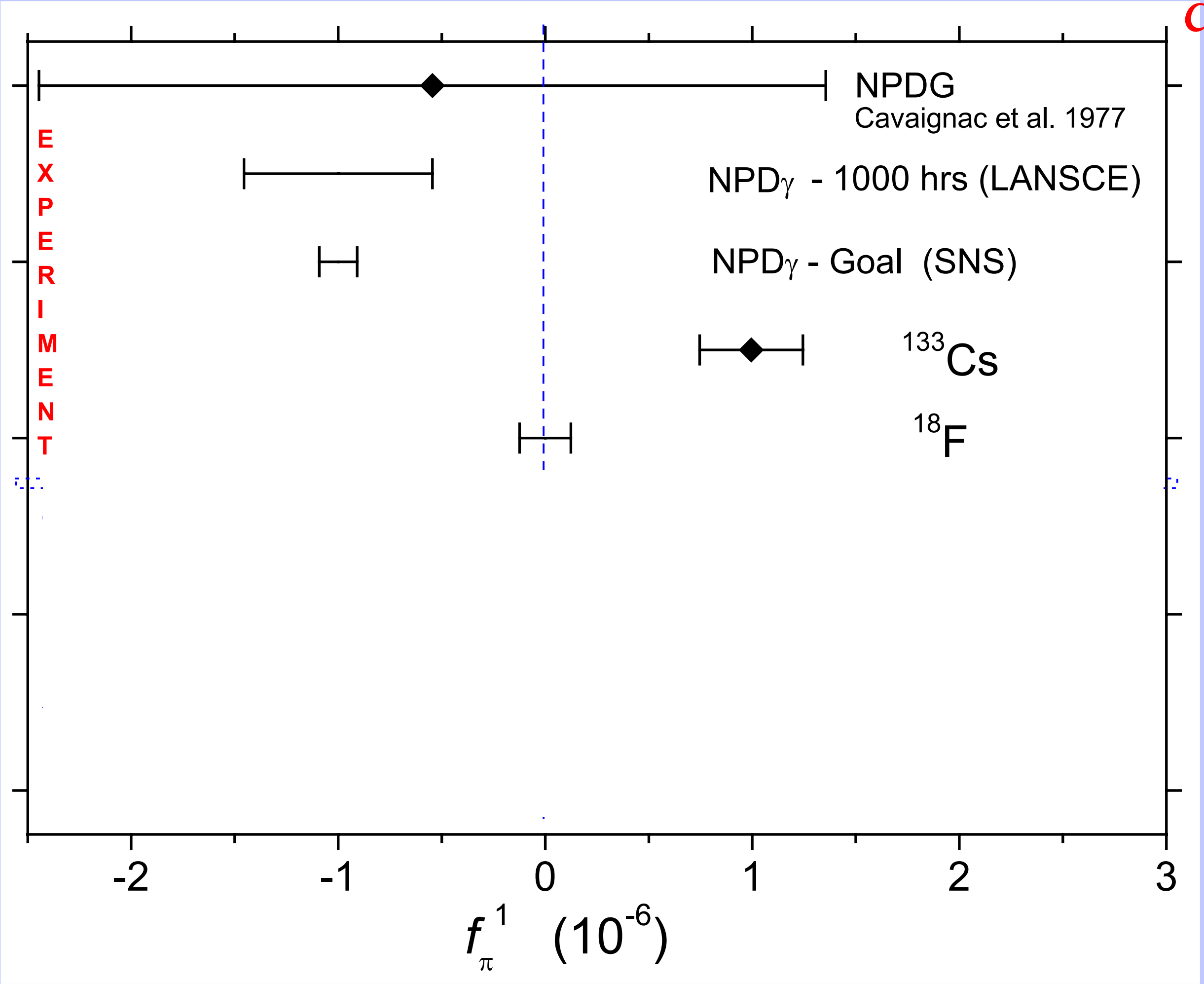
DDH
$$A_\gamma = \hat{S}_n \cdot \hat{k}_n = \frac{1}{P_n} \frac{N_u - N_d}{N_u + N_d} \approx -0.11 f_\pi \approx -5 \times 10^{-8}$$

EFT
$$A_\gamma = -0.107\, \rho_t m_N$$

- **Negligible (less than 1%) contributions from ρ, ω, 2π exchanges**
- **No uncertainty from nuclear wave functions**

Constraints on Weak N-N Coupling

- Previous determinations of $f_p = \sqrt{32} H_\pi^1 / g_{\pi NN}$ disagree:



contradictory results

anapole moment

photon polarization

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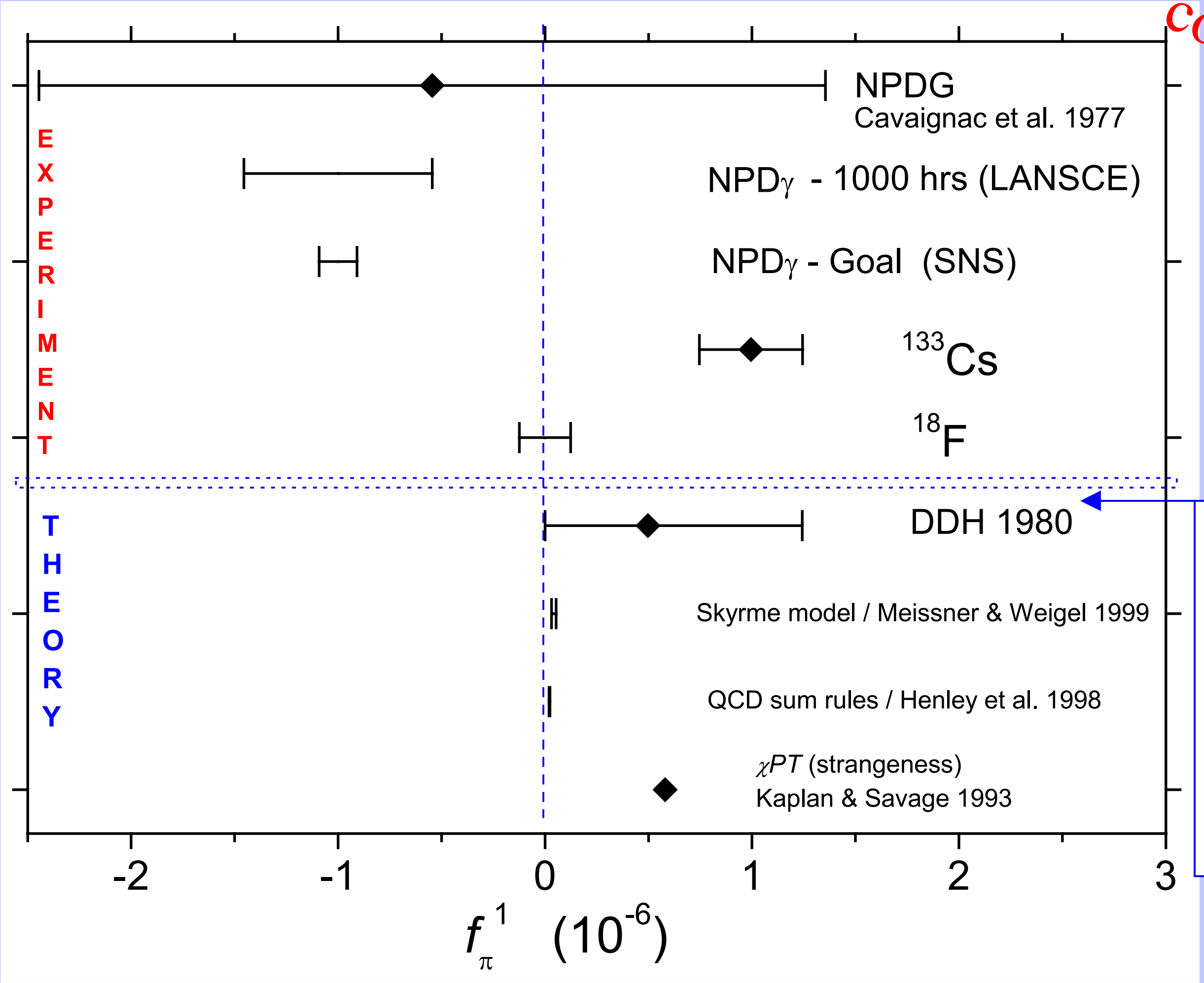
contradictory results



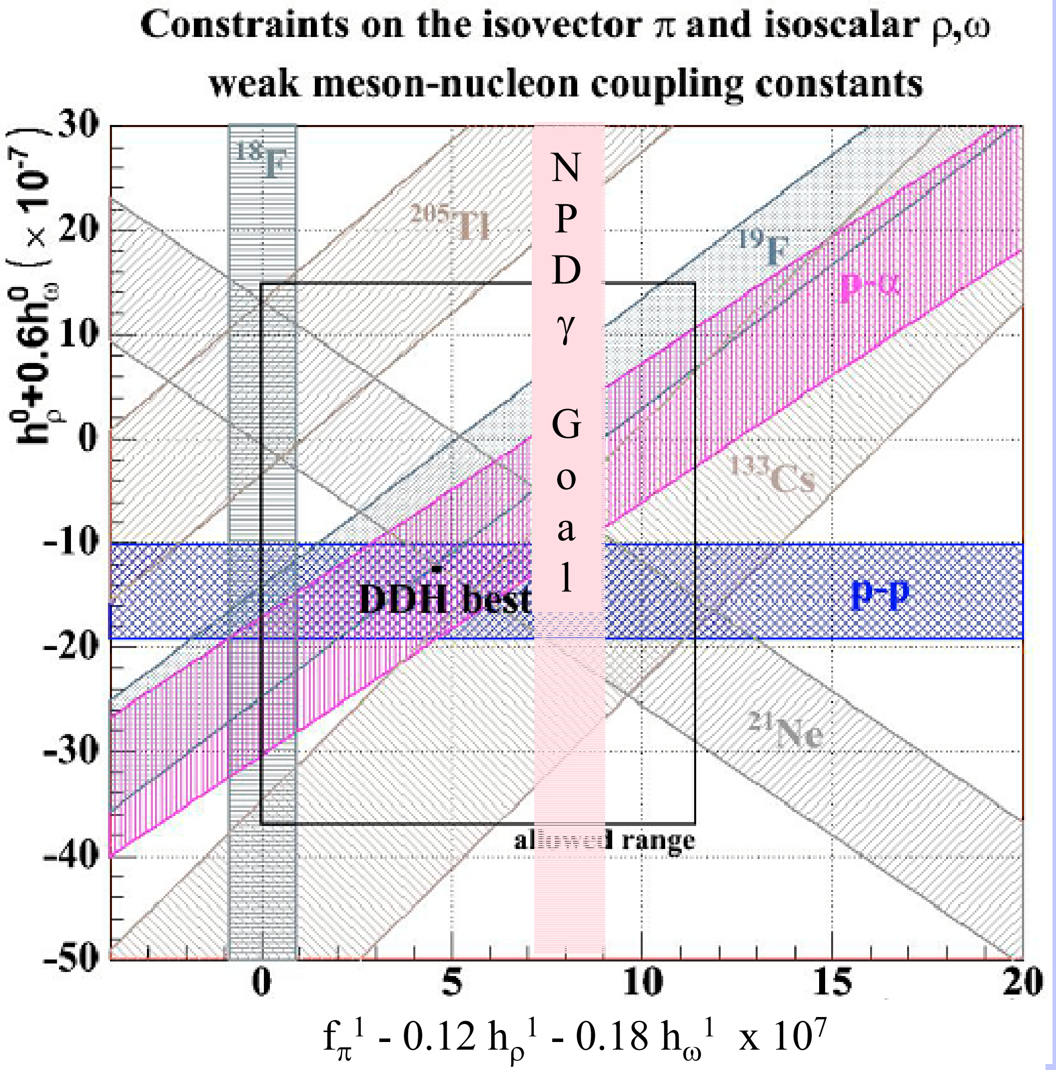
anapole moment

photon polarization

DDH
Meson Exchange Currents
reasonable theoretical range
0 - 1.14
best value 0.45

Constraints on Weak N-N Coupling

In reality experiments determine a linear combination of couplings (In npdg other couplings than f_π are negligible)

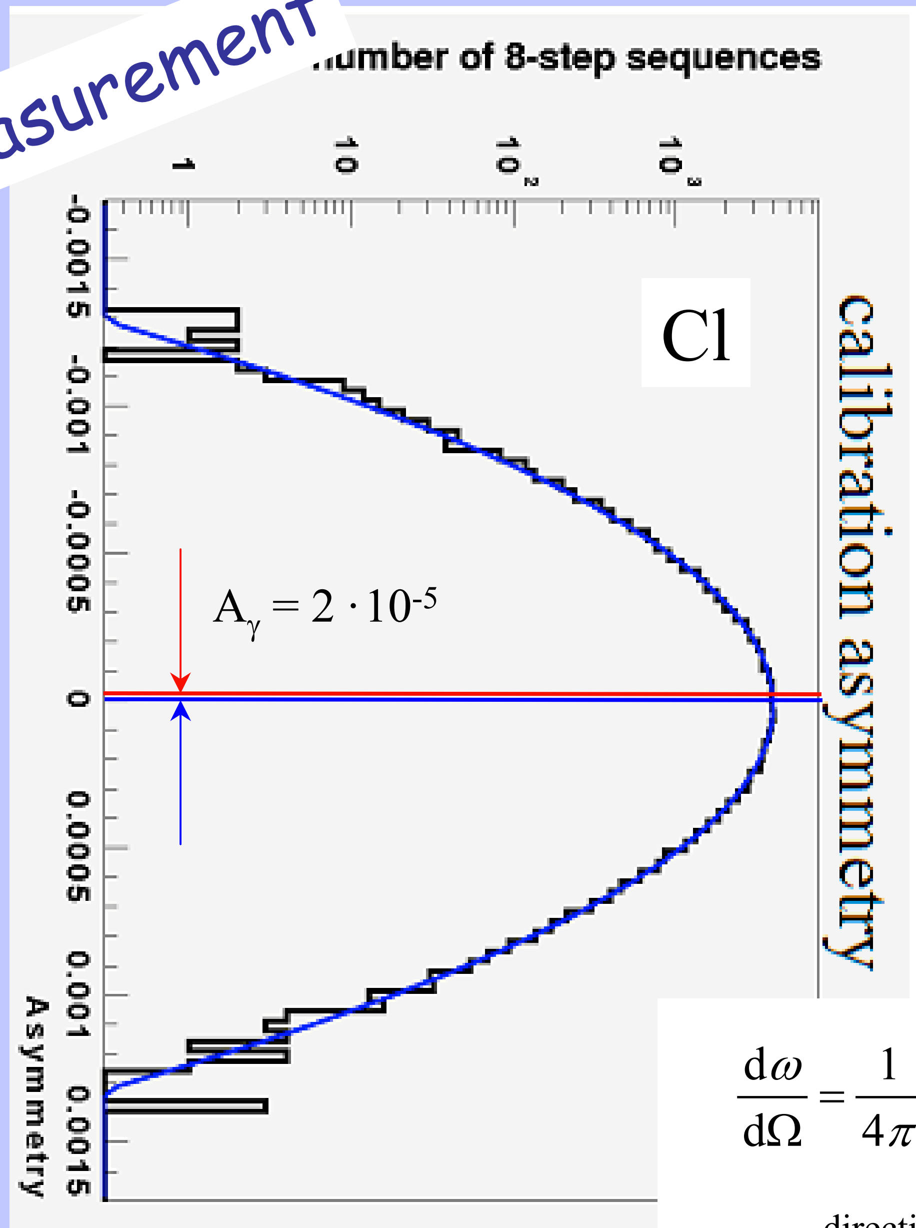


Observables on this plot:

- Nuclear anapole moment κ
  ^{205}Tl, ^{133}Cs
- Longitudinal analyzing power A_z
  p-p, p-α
- Photon polarization P_γ
  ^{18}F, ^{21}Ne, $\vec{\gamma} d \to pn$
- Directional gamma asymmetry A_γ
  ^{19}F, $\vec{n} p \to d\gamma$

Typical Measurement

NPDG
GOAL = 10^{-8} !!!



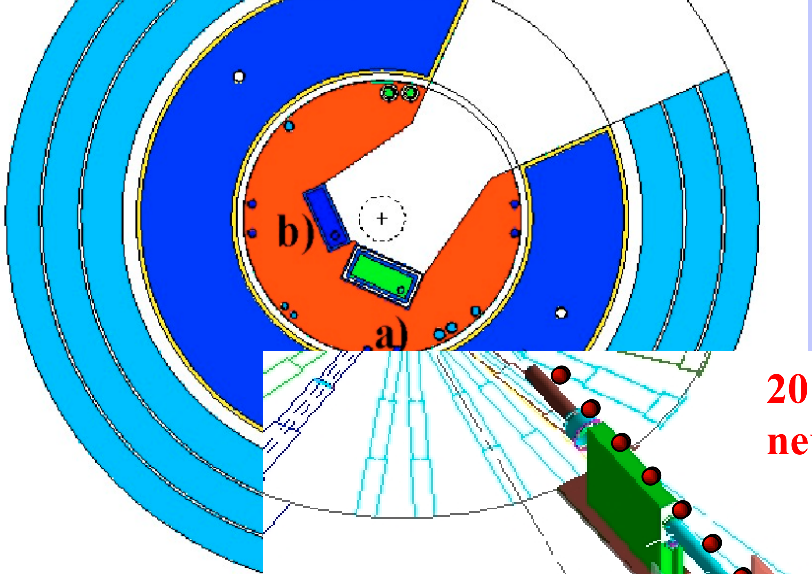
$$\frac{d\omega}{d\Omega} = \frac{1}{4\pi}\left(1 + A_\gamma \cos(\Theta_{s_n \cdot k_\gamma})\right)$$

direction of n spin $\vec{s}_n$ and
photon momentum $\vec{k}_\gamma$

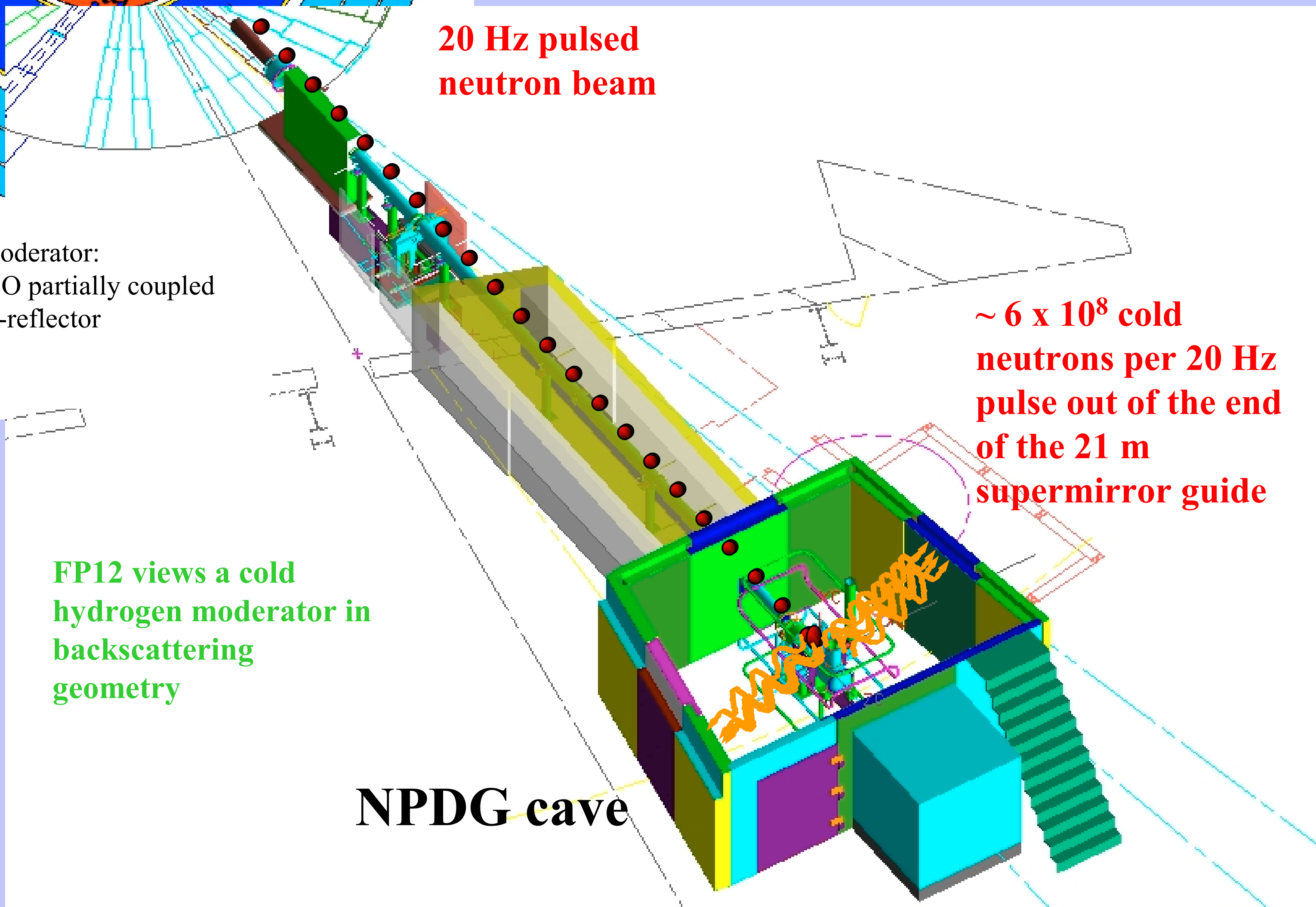
How do we perform the measurement of the $np \rightarrow d\gamma$ process ?

Neutron Source

L
A
N
S
C
E



Liquid H2 coupled moderator:
a) liquid H2 b) H2O partially coupled
c) Be-reflector d) Pb-reflector



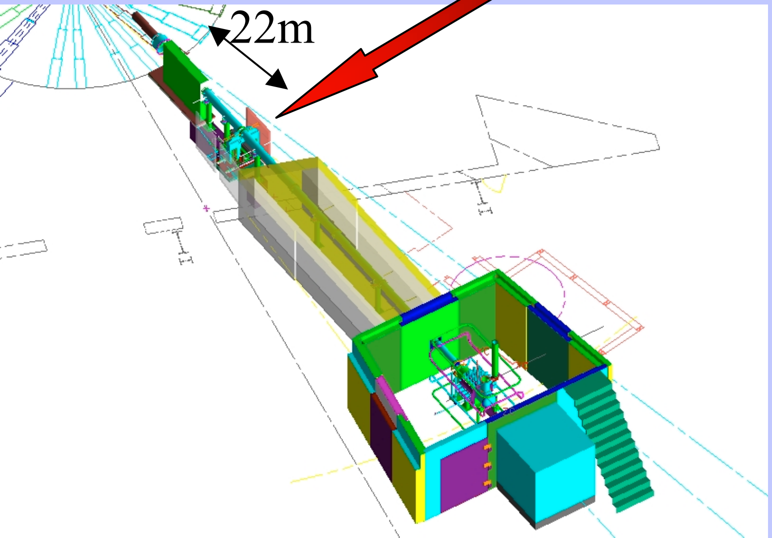
20 Hz pulsed neutron beam

~ 6 x 10^8 cold neutrons per 20 Hz pulse out of the end of the 21 m supermirror guide

FP12 views a cold hydrogen moderator in backscattering geometry

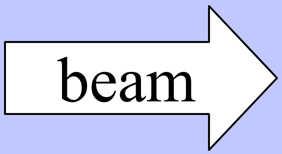
NPDG cave

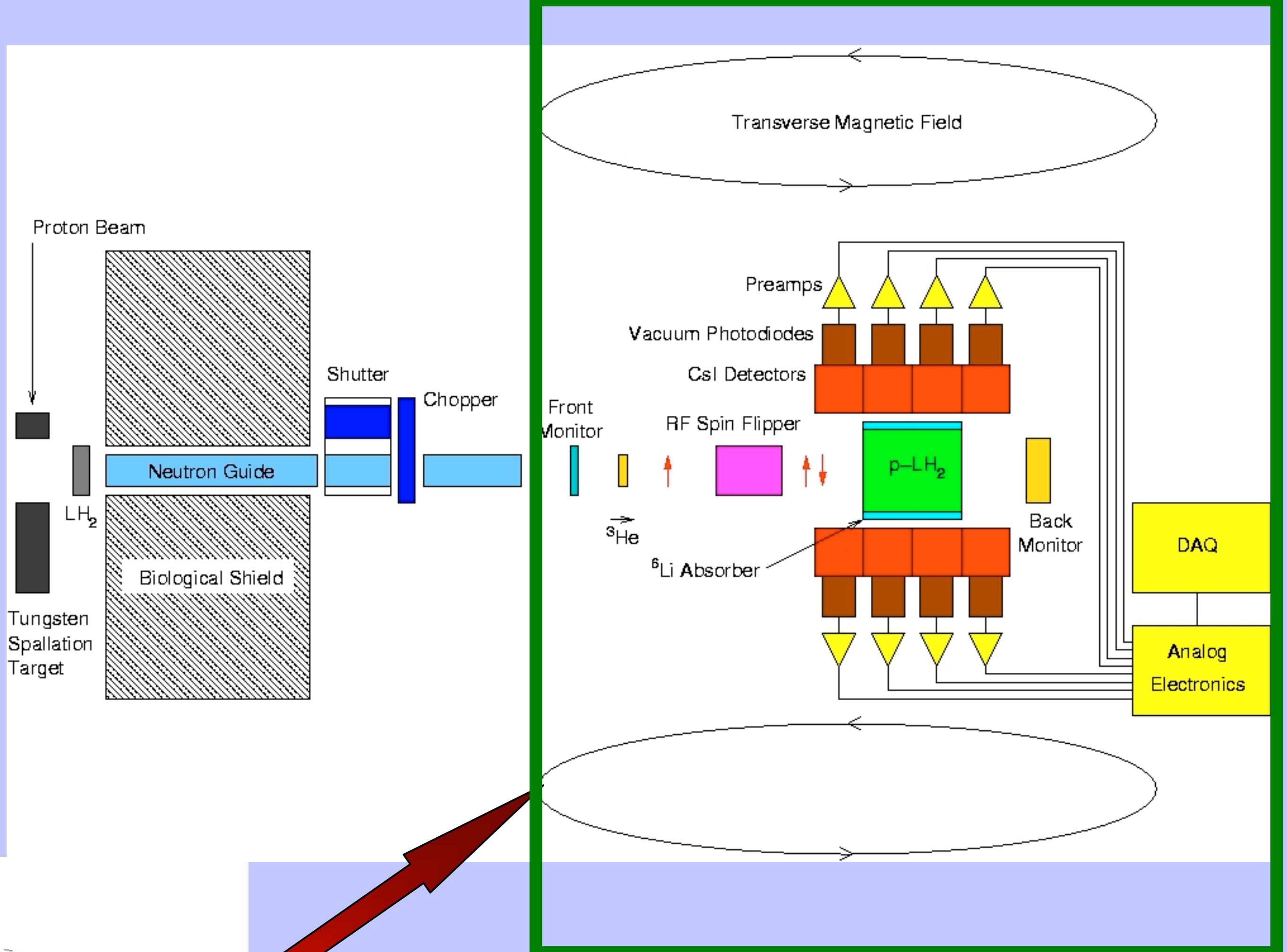
Frame Definition Chopper

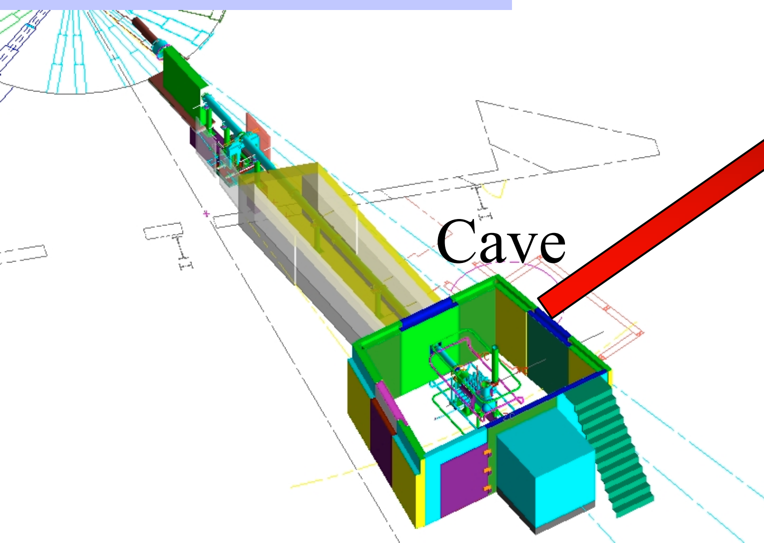


- Pulsed beam: neutron time-of-flight determines neutron velocity, energy
- PV asymmetry is independent of energy
- Very slow neutrons can overlap with faster neutrons from later pulse
- Chopper rotor coated with Gd_2O_3 absorbs slow neutrons up to 30 meV, opens window for faster ones
- up to 1200 RPM
- settings: opens with n-pulse onset
  4 ms later open , closes after 30 ms, 4ms later totally closed

Experiment Setup







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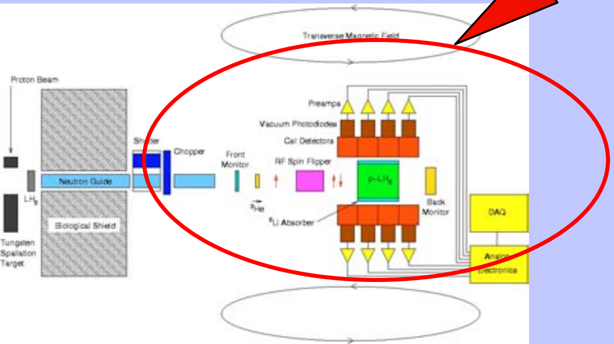
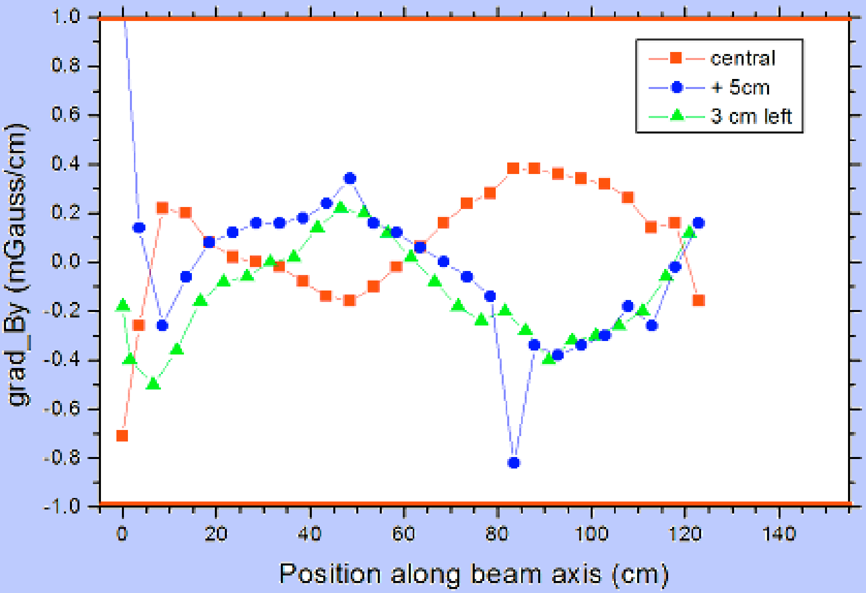
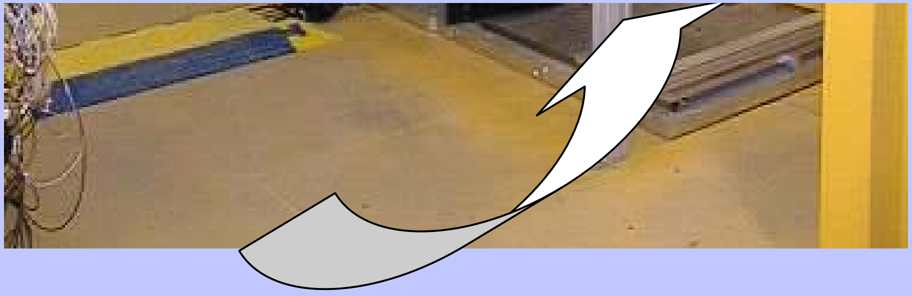


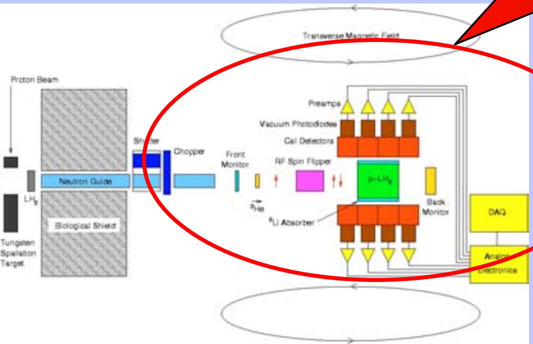
Experiment Setup
Guide Field

whole setup contained in 10 Gauss guide field to prevent Stern-Gerlach steering of neutrons

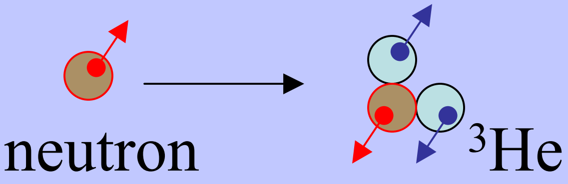
requires gradient ≈ 1 mGauss / cm or smaller

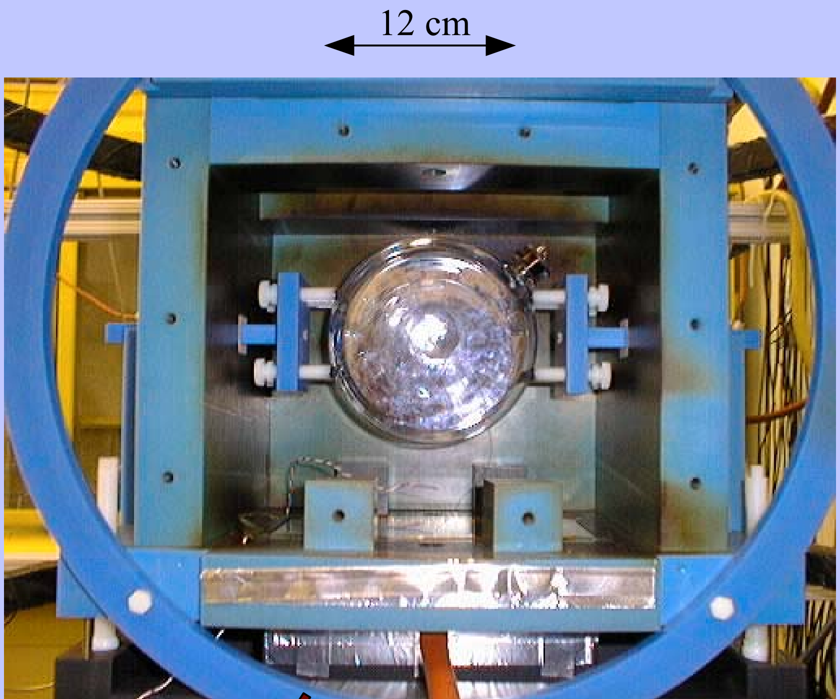


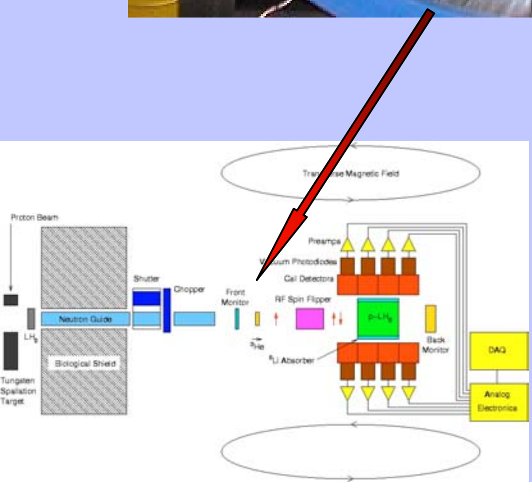




Neutrons are polarized by Optically-Polarized ^{3}He Spin Filter



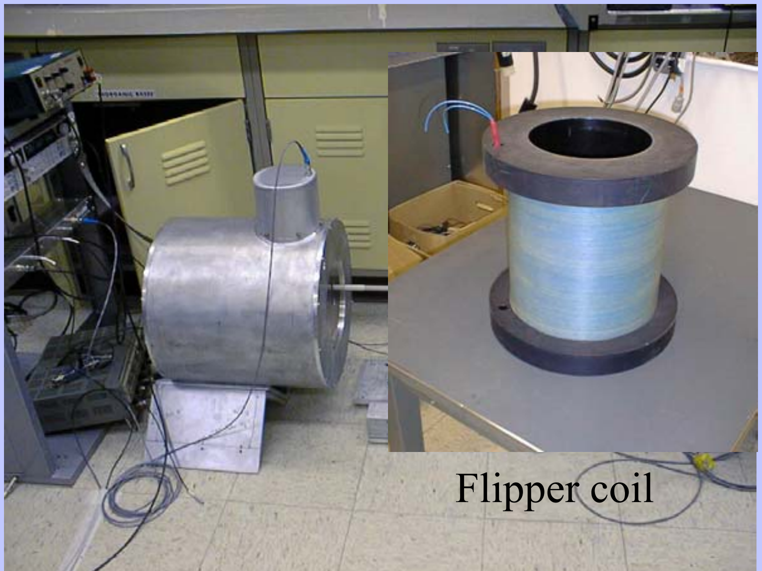


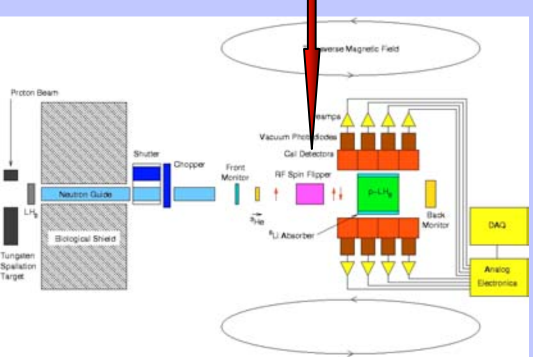


^{3}He neutron spin filter:

- In a ^{3}He cell Rb atoms are polarized by laser light. Through spin exchange, ^{3}He gas is nuclear polarized.
- neutron capture cross section of the ^{3}He singlet state is much larger than the triplet state. (10^4 difference)
- Therefore, neutrons with spin antiparallel with ^{3}He spins are absorbed and neutrons with spin parallel with ^{3}He spins are transmitted → neutron spin filter

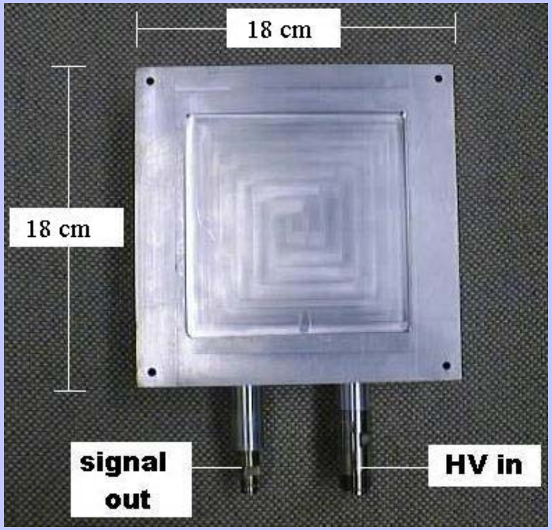
Spin Flipper

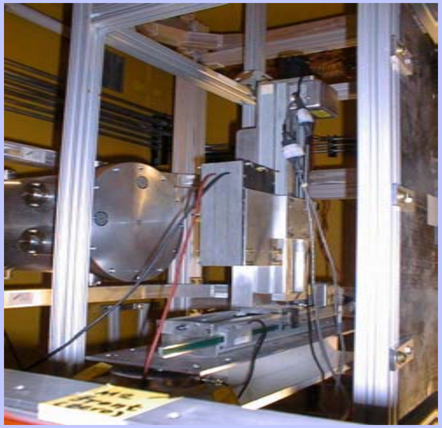


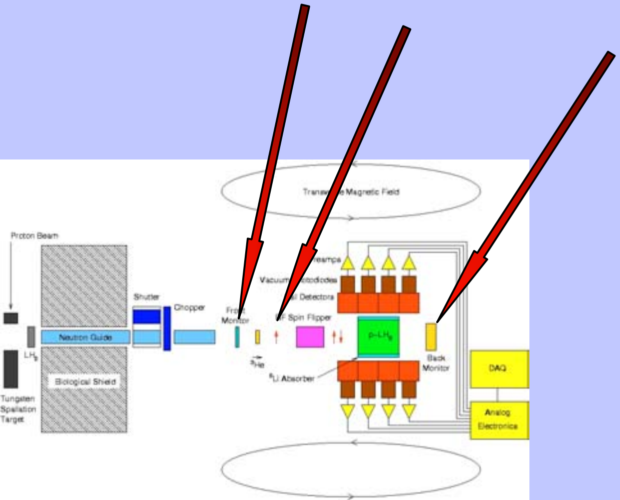


- In a DC magnetic field B_o, a resonant RF magnetic field ($B_1 \cos \omega t$) is applied for a time $\tau = 1/\gamma B_1$, to precess the neutron spin, around B_1, by π. 20 Hz pulse pattern
- $B_1(t) \propto 1/TOF$, for reversing neutron spin in wide energy range (~0.5-50 meV).
- RF spin flipper is the main control of systematic errors. Spin flip sequence is "↑↓↓↑↓↑↑↓".
- Grad. $\partial B_z / \partial z < 1$ mgauss/cm $\Rightarrow$ no Stern-Gerlach steering force ($\mu . \nabla B$) → no false asymmetry.
- High maximum spin reversal efficiency for $0 < E_n < 100$ meV, ~ 95% for $E_n = 4$ meV

Beam Monitors







3 beam monitors used to measure

i) neutron flux out from the guide

ii) beam polarization

iii) ortho/para ratio in LH_2 target

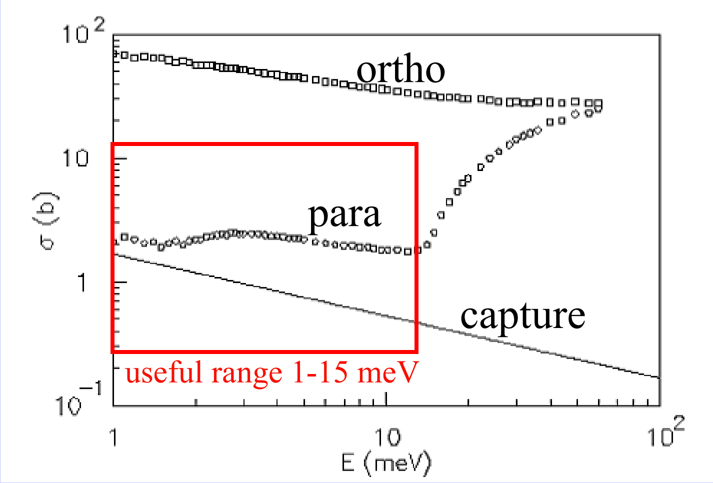
$n + {}^3He \rightarrow p + t + 765$ keV $\rightarrow$ ionizes gas mixture
$[{}^3He + {}^4He(\sim.5\text{ atm}) + N_2(\sim.5\text{ atm})]$

Ratio of ^3He to ^4He (~5% to 100%),

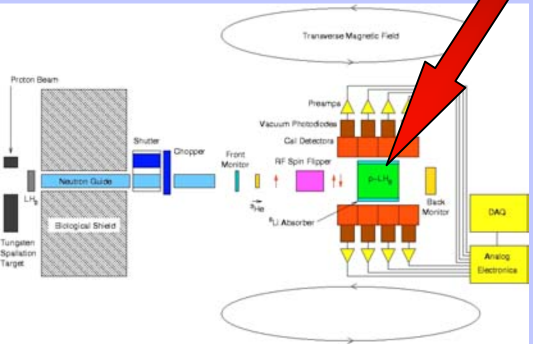
$\sigma_{abs}({}^3He) >> \sigma_{abs}({}^4He)$

20-liter Liquid Para-Hydrogen Target

- To maintain neutron spin in scattering a para- hydrogen target is required.
- The 30 cm in diameter and 30 cm long target captures 60% of incident neutrons.
- At 17 K only 0.05% of LH_2 is in ortho state $\rightarrow$ 1% of incident neutrons will be depolarized.
- Target cryostat materials selected so that false asymmetries < 10^{-10}.



Neutron mean free paths at 4 meV in
- ortho-hydrogen is $\lambda =$ 2 cm,
- para-hydrogen is $\lambda =$ 20 cm
- for a *n-p* capture is $\lambda =$ 50 cm.



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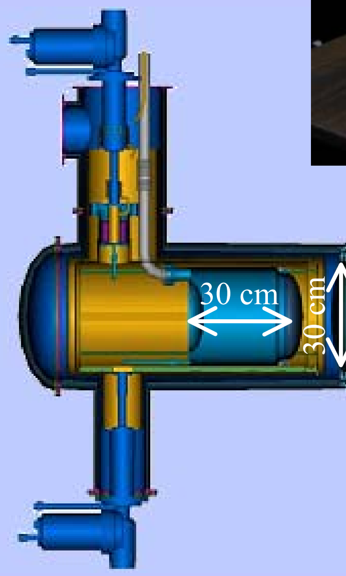
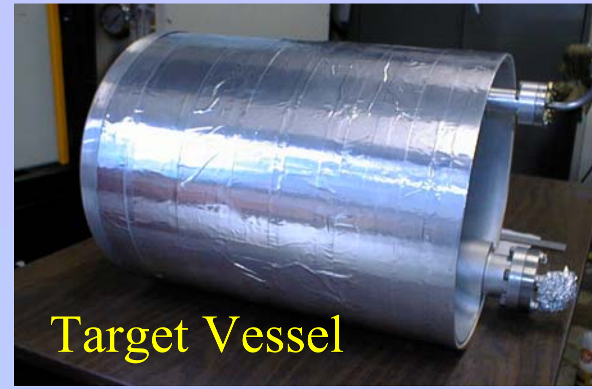
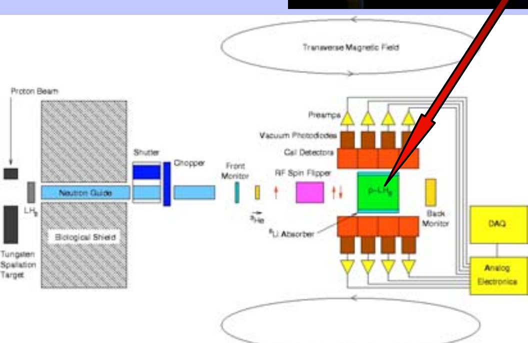




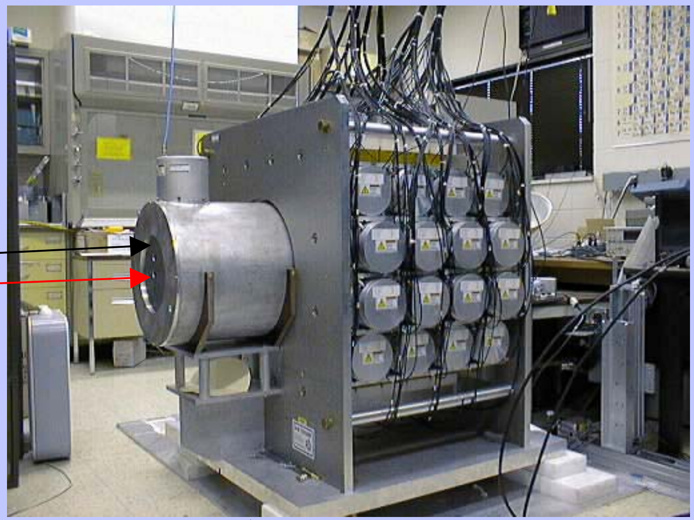


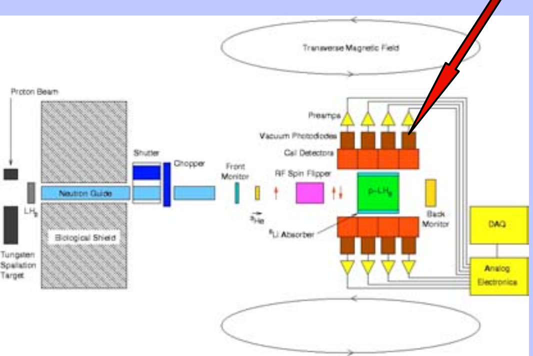
- presently being tested
- has to be LANL safety commissioned
- ready end of 2005

CsI detector array

spin flipper

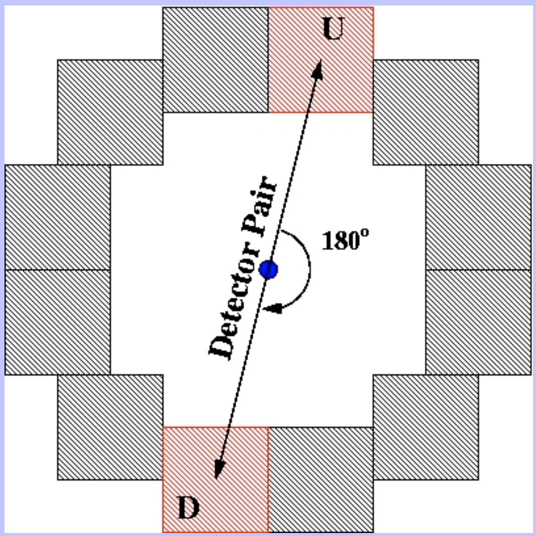
beam

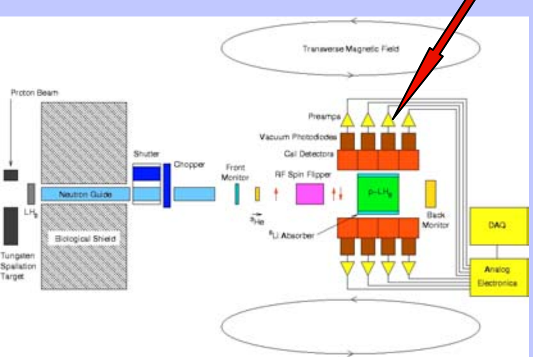




- 5×10^7 γ's/pulse are expected into the detector array → Detection in current mode. --- Electrical noise kept significantly smaller than counting statistics / use sum + difference amplifier
- The 3π detector array employs 48 CsI (Tl) scintillator crystals ($15 \times 15 \times 15 cm^3$), each coupled with a 3-inch vacuum photo-diode.
- Gain provided by low noise solid-state preamplifiers. Gains are magnetic field insensitive.
- Interaction length of a 2.23 MeV γ ray in CsI ~ 5.5 cm. ~95% of γ's stop in 15 cm.

CsI detector array





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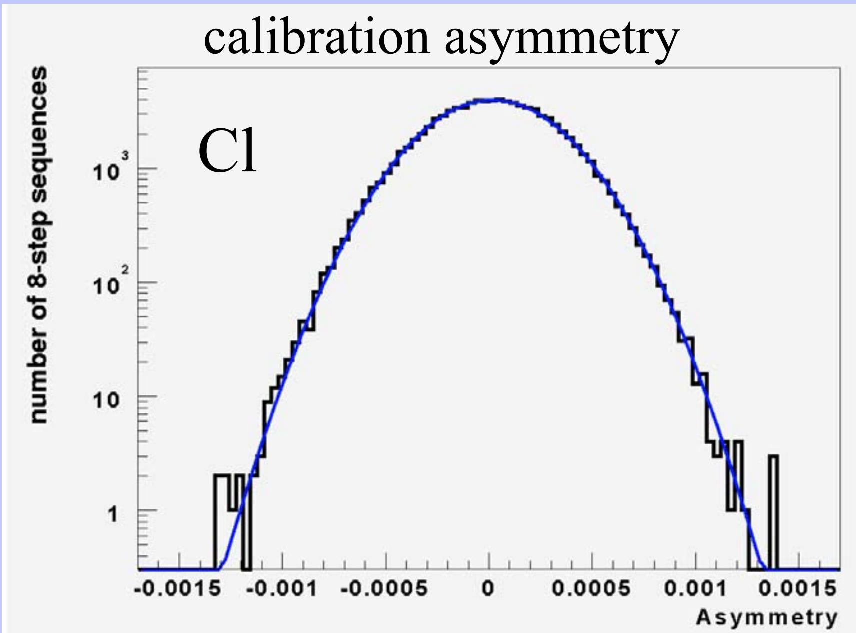
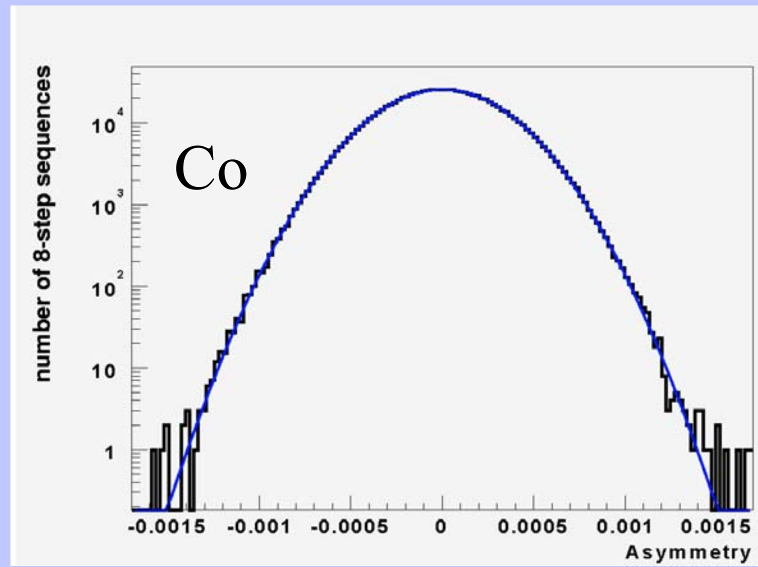
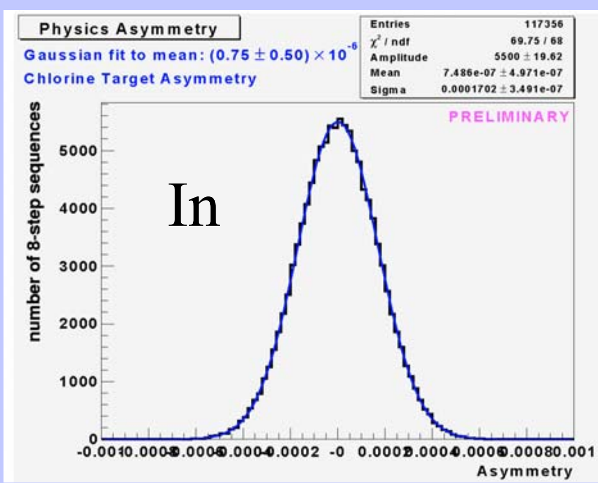
First Results

- engineering materials check
- study of hadronic weak interaction in atoms with A ~ 50 (experiment is running)



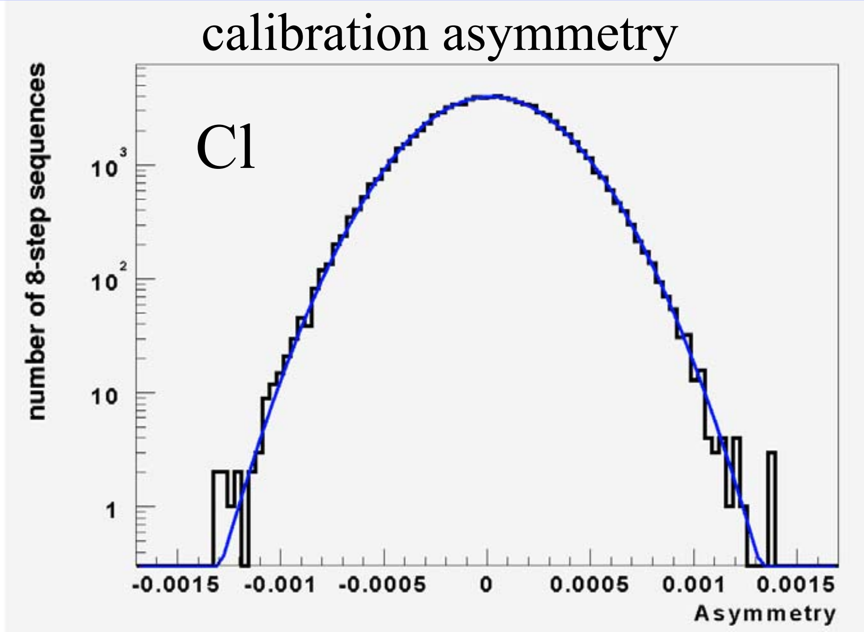


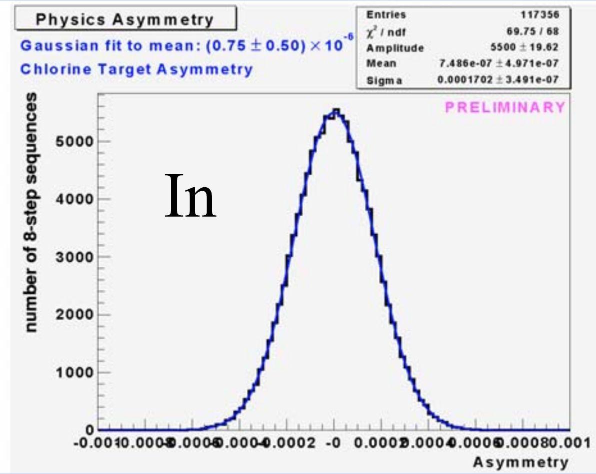


$$\frac{d\omega}{d\Omega} = \frac{1}{4\pi}\left(1 + A_\gamma \cos(\Theta_{s_n \cdot k_\gamma})\right)$$

direction of n spin $\vec{s}_n$ and
photon momentum $\vec{k}_\gamma$

First Results





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- study of hadronic weak interaction in atoms with A ~ 50 (experiment is running)

Targets and Asymmetries

- In:
  $A_\gamma = (-6.8 \pm 3.0) \times 10-7$:Estimated - A_γ RMS - 1.0×10^{-6}
- Mn: $A_\gamma = (5.3 \pm 7.8) \times 10-7$:Estimated - A_γ RMS - 1.3×10^{-7}
- Sc: $A_\gamma = (-7.0 \pm 2.8) \times 10-7$
- Co: $A_\gamma = (6.1 \pm 3.1) \times 10-7$
- Ti: $A_\gamma = (7.1 \pm 4.0) \times 10-7$
- Al: $A_\gamma = (-0.02 \pm 3) \times 10-7$:Estimated - A_γ RMS - 4×10^{-8}
- Cl: $A_\gamma = (-21 \pm 1.6) \times 10-6$

thanks to PhD students M.Dabagian & R.Mahurin

Summary

- npdγ is ready end of this year for production data

- 2006 @ LANSCE $A_\gamma < 10^{-7}$

- move to SNS

  start data taking in 2008

  -> $A_\gamma < 1 \cdot 10^{-8}$ at FNPB

The NPDγ Collaboration

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Thanks
for your attention !

  

Systematic Issues

- Physics - correlated with neutron spin:
  - activated materials - emit γs in β-decay
  - Stern-Gerlach steering
  - L-R asymmetry
    - *n* - *p* elastic scattering
    - n - p parity allowed asymmetry
    - Mott-Schwinger scattering
- Instrumental sources
  - electronics, stray magnetic fields, gain stability
- Monitoring:
  - Null test at E_n > 15 meV and at end of each pulse.